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Optimal Power Management for the UTS Plug-in Hybrid Electric Vehicle

by

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I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Salisa binti Abdul Rahman

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ABSTRACT

There is a great potential for significant improvement to be made in energy efficiency and all-electric drive performance of the different types of existing powertrain architectures, such as: 1) traditional internal combustion engine (ICE) powered vehicles; 2) electric vehicles (EVs); 3) hybrid EVs (HEVs), which consist of three types according to the power flow: 1) series; 2) parallel; and 3) series-parallel; and 4) plug-in HEVs (PHEVs) through implementing innovative technologies. Many major car manufacturers have been making great efforts to develop an alternative form of transportation that can offer better solutions to reduce the serious undesirable impacts to the environment and economy. The new type of vehicles will win quick acceptance in the marketplace because of the current high fuel cost and greenhouse gas emissions. Today PHEV is more promising in energy efficiency than HEVs if the energy storage system (ESS) is recharged by electricity generated from clean energy sources, such as wind and solar.

Most of the existing powertrain architectures need two electric machines (EMs) to function as an electric motor and generator respectively. To improve the vehicle all-electric drive performance and energy efficiency, the University of Technology, Sydney (UTS) PHEV is proposed, which is a series-parallel type. The UTS PHEV requires only a single EM in its powertrain to function as an electric motor or generator in different time intervals controlled by a special energy management strategy (EMS). This powertrain uses two electric energy sources, which are battery and ultracapacitor packs that can work together

to maintain the state of charge (SOC) at a high level in order to improve vehicle all-electric drive performance and energy efficiency.

While the main drive power of the UTS PHEV comes from the electric motor supplied by the battery pack, the ICE is needed as a back-up and auxiliary power source. Adding the ultracapacitor pack to this powertrain can more effectively capture the regenerative braking energy resulting in better energy efficiency and meet large power demand from the electric motor, providing better dynamic drive performance and all electric range (AER). In comparison with the HEVs, the size of the ICE can be reduced since it is needed just as auxiliary drive when there is a need for extra power during fast acceleration or hill climbing and for battery charging when the SOC is low during long distance drives.

In this work, through a power flow analysis of the powertrain, the vehicle main components were sized according to the vehicle parameters, specifications and performance requirements to meet the expected power requirements for steady state velocity of an average typical 5-passenger car. After the sizing process, the components were selected based on the parameters and specifications of each component. Then, the model of individual components that make up the overall structure of the UTS PHEV powertrain, known as UTS PHEV code are derived and implemented numerically in the MATLAB/SIMULINK environment to study their operational performance in various drive cycles measured under real-life conditions. The accuracy of the model is verified and validated by a comparison between the simulation results from the UTS PHEV and the Advanced Vehicle Simulator (ADVISOR) codes during a number of standard drive cycles.

The simulation results of the selected subsystems from both codes are compared and the advantages and disadvantages are discussed.

Extensive analysis has been conducted on the fuel economy, emissions: 1) hydro carbon; 2) carbon monoxide; and 3) nitrogen oxides, electrical consumption, AER, operation cost and total lifetime cost computed for different standard drive cycles, developed low and high density traffic patterns drive cycles and example of high congestion drive cycle. The main objective of the test procedure design is to optimize the power and energy demands throughout the system and compare the fuel economy, emissions, electrical consumption, AER, operation cost and total lifetime cost of the UTS PHEV code with the existing powertrain architectures by satisfying the test procedure inputs. The power balance requirements between the battery and ultracapacitor packs in its ESS is also studied by testing the effectiveness of the developed EMS using the three different selected standard drive cycles.

The optimization of a power flow management in the UTS PHEV powertrain via parametric study and genetic algorithm method of optimization is implemented in this work for several standard drive cycles. The objective of this optimization is to obtain the best design variable values by improving the chosen objective functions while satisfying the design constraints. Based on the optimization results, there is a significant improvement in fuel economy and emissions and the design variable values are within reasonable and expected range depending on the applied drive cycles.

It can be concluded that the proposed UTS PHEV powertrain can achieve the desired all-electric drive performance and improve the energy efficiency by using only one EM through the implementation of a more sophisticated EMS and ultracapacitor pack so as to reduce the negative impacts on global warming, oil depletion and the compulsory standard on fuel economy and emissions.

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F	driving force
m	vehicle mass
a	acceleration
g	gravitational acceleration
c_{rr}	rolling resistance
θ	the angle of the road
ρ	air density
c_d	drag coefficient
A	frontal area
v	velocity
P_{req}	power required
P_{aero}	power to overcome aerodynamic drag
P_{roll}	power to overcome rolling resistance
P_{grade}	power for ascending
P_{accel}	power for acceleration
P_{EM}	power of the EM
P_{ICE}	power of the ICE
P_{ESS}	power of the ESS unit
P_B	power from battery pack
P_{UC}	power from ultracapacitor pack
$E_{battery}$	battery storage capacity
V_{ocpack}	open circuit voltage of the battery pack
R_{pack}	internal resistance of the battery pack
I_{out}	output current calculation
V_{out}	output voltage
P_D	power demand
V_{oc}	open circuit voltage
R_{chg}	charging resistances

R_{dis}	discharging resistances
V_{out}	voltage at the terminals
$K_{num\_cell\_series}$	number of cells in the ultracapacitor modules that are connected in series
$K_{num\_cell\_parallel}$	number of cells in the ultracapacitor modules that are connected in parallel
V_{min}	minimum voltage
V_{max}	maximum voltage
P	power supplied
ω	rotating speed
τ	torque
τ_{output}	output torque
I_{motor}	inertia moment
α	angular acceleration
R	wheel radius
τ_{gear}	gearbox torque
Eff	efficiency
τ_{EM}	EM torque
ω_{gear}	gearbox speed
ω_{EM}	EM speed
ESS_{SOC}	ESS SOC
ESS_{SOChi}	high ESS SOC
$P_{converter,max}$	maximum power of power converter
$P_{EM,max}$	maximum power of EM
$P_{ICE,opt}$	optimum power of ICE
R_{int}	battery internal resistance
η	peak efficiency
D	distance
V_{fuel}	volume of fuel consumed
E_{charge}	required electrical recharge energy

$E_{gasoline}$	constant equal to 33.44 kWh/gallon
ΔSOC	difference between the initial and the target SOCs
B_{mod}	battery module
B_{SOChi}	high battery SOC
B_{SOClo}	low battery SOC
UC_{mod}	ultracapacitor module
UC_{SOChi}	high ultracapacitor SOC
UC_{SOClo}	low ultracapacitor SOC

NOMENCLATURE

ICE	internal combustion engine
IPCC	intergovernmental panel on climate change
GHG	greenhouse gas
CO_2	carbon dioxides
CAFE	corporate average fuel economy
CO	carbon monoxide
HC	hydro carbons
NO_x	nitrogen oxides
PM	particulate matter
mpg	miles per gallon
GM	General Motors
HEVs	hybrid electric vehicles
EPA	environmental protection agency
UTS PHEV	University of Technology, Sydney plug-in hybrid electric vehicle
AER	all electric range
GA	genetic algorithm
EMS	energy management strategy
EM	electric machine
AT	automatic transmission
ADVISOR	advanced vehicle simulator
SOC	state of charge
ESS	energy storage system
EV	electric vehicle
PHEV	plug-in hybrid electric vehicle
INDIAN URBAN	Indian urban driving cycle
INDIAN HIGHWAY	Indian highway driving cycle
UDDS	urban dynamometer drive cycle

HWFET	highway fuel economy test
CI	compressions ignition
SI	spark ignition
ZEVs	zero emissions vehicles
APU	auxiliary power unit
THS	Toyota hybrid system
PCM	plug-in conversion module
SOHC	single overhead camshaft
CVT	continuous variable transmission
MT	manual transmission
PSAT	powertrain systems analysis toolkit
GUI	graphical user interface
NREL	national renewable energy laboratory
DOE	department of energy
SLA	sealed lead-acid
NiCd	nickel-cadmium
NiMH	nickel-metal hydride
Li-ion	lithium-ion
GM	general motors
PI	proportional and integral
Ah	ampere-hour
OWC	one-way clutch
US06	high speed and high acceleration component of the U. S. EPA's supplemental federal test procedure
NEDC	new European drive cycle
CSHVR	city-suburban heavy vehicle route
LA92	Unified LA92
FTP	U. S. EPA federal test procedure
UDDSHDV	urban dynamometer driving schedule for heavy-duty vehicles
BP	brake pressure

PCT	partial charge test
FCT	fully charge test
DIRECT	divided rectangles
SA	simulated annealing
PSO	particle swarm optimization
FDR	final drive ratio